August 30, 2002

Space Charge Neutralization of Pulsed Ion Beams by Pulsed Metal Plasmas

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I. Background

The background for this effort was explained in white paper and FY2003 LDRD proposal. In essence, the positive space charge of a pulsed ion beam delivered from an accelerator needs to be compensated by electrons in order to minimize beam blowup to preserve low emittance.

The beam can capture electrons when passing through a plasma that has low density of heavy particles. Ideally, no neutral atoms or molecules are in the plasma. Fully ionized metal plasma from one or more pulsed vacuum arcs can be used. Pulsed metal plasma can easily been generated using vacuum arc plasma sources as such those previously developed at Berkeley Lab. The density and duration of the plasma can be adjusted in a very wide range. For example, aluminum plasma of density 10^8-10^{12} cm^{-3} can be produced in pulses of 1-1000 μs by selection of suitable arc current and discharge geometry.

In the work done in July and August 2002 at the Plasma Applications Group, AFRD, filtered arc sources have been custom designed and manufactured for the tests at Berkeley Lab's HIF facility. In the following, the equipment is briefly described and characterized.

II. Plasma Generator

The plasma sources are of the "minigun" type [1], comprised of a replaceable cathode rod of ¼" diameter and about 1" length, a ceramic insulator as part of the cathode assembly, a grounded anode body. The source is coupled to an open macroparticle and neutral atom filter [2], which is essentially a copper coil of flat cross section (Figure 1). Filter and source are electrically in series, allowing us to operate both with one power supply. Two of such source/filter assemblies are installed to obtain symmetry in the plasma distribution. The consumable cathode is made from aluminum because deposition of aluminum on the beamline's components does not introduce foreign material. The lifetime of the cathode before maintenance is estimated to be about 100,000 arc pulses. After this time, the cathodes should be inspected and replaced if needed. Source and filter are not actively cooled, and therefore the repetition rate should be limited to a maximum of 0.5 p.p.s., even is the power supply is capable of a much faster rate.

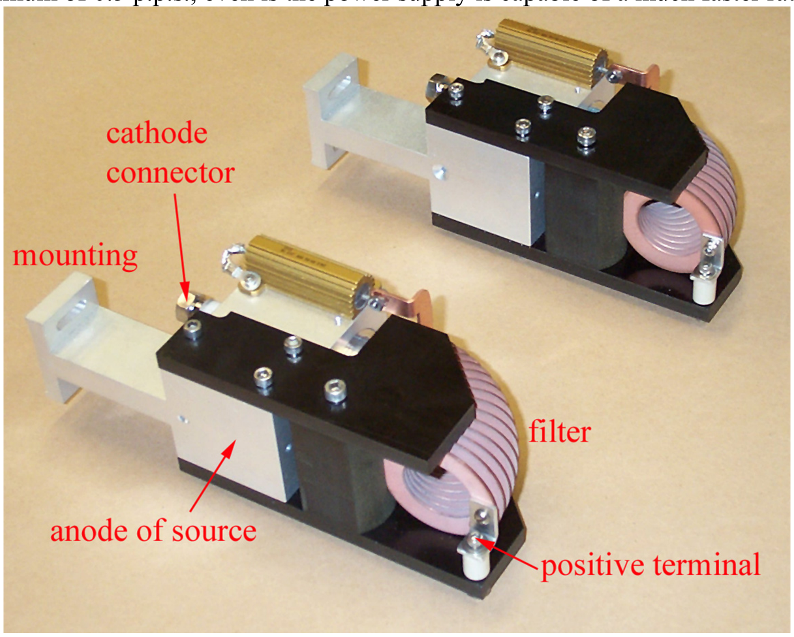

Figure 1: Two plasma source units after manufacturing.

III. Power Supply
As a power supply we use a pulse-forming-network (PFN) of about 1 Ohm impedance [3]. It is equipped with a high-current SCR switch. The switch can switch ON but goes only in the OFF state when the current goes through current-zero. The duration of such current pulse is determined by the PFN hardware (capacitors and coils). The ON timing is determined when a pulse of 5-8 Volts shows a negative slope at the BNC connector labeled “gate in.” Here it does not matter if the signal goes from say +5 Volt to O or from O to –5 Volts. The PFN is charged by a DC charging supply. We use 3 kV, 100 mA Glassman supply. The PFN model 5.3 can handle a maximum voltage of 3 kV. A minimum voltage of 1.5 kV is recommended: at lower voltages the arc may not trigger or the current goes too slowly to zero thus the SCR may shut off (see Trouble Shooting). Tests have been done at a charging voltage of 2.0 kV.

The charging supply is connected to the PFN via a protection resistor (about 500 Ω, inside a box for safety reasons). The purpose of the resistor is to dampen and voltage spikes or feedback into the charging supplies. With the resistor the current meter circuit of the charging supply tend to be damaged.

The cables are color-coded. Red indicates plus (anode) and black indicates minus (cathode).

IV. Power Requirement
All components (PFN and charging supply) use standard 110 V AC. No other power or water or gas is required.

V. Interlock
The 110 V AC should be supplied from interlocked power outlet. Loss of 110 V will not only stop charging the PFN but also will close the fail-safe drop switch in the PFN unit, thereby short-circuit the capacitors of the PFN.

The Classman power supply has an additional provision for interlocking. The device will only deliver high voltage power if the pins 2 and 3 are connected. One can remove the jumper between 2 and 3 and use this circuit for interlocking. Interruption will cause a shutdown of charging but it will not secure the capacitors of the PFN.

VI. Grounding
The ground of the circuit is given by the anode, which is mounted to the grounded vacuum chamber. PFN-chassis, charging supply, and chamber must be grounded.

VII. Trouble Shooting
1. In the unlikely event the SCR does not shut off, the charging supply will show low voltage and maximum current. Action: Shut down the charging voltage, waiting 10 sec to allow the current to go to zero, switch back on. Make sure the PFN is fully charged before the next arc trigger signal is given: check the charging state of the PFN using the voltmeter at the PFN front panel.
2. If the arc does not trigger, or only one of the arc triggers, shot off the system. Disconnect the power connectors from the vacuum feedthroughs. Measure the resistance between cathode connector and anode connector for each plasma gun. The resistance can vary in a wide range but should not exceed 100 kΩ. If it is higher, the conducting film at the cathode ceramic is insufficient and needs to be replaced.
3. In case of question, contact Andre Anders, Tel. (510) 486-6745 or by e-mail aanders@lbl.gov

IX. Performance
In a first round of tests, the two source units (plasma gun and filter) were mounted in a high vacuum chamber at Bldg. 53 of Berkeley Lab (Figure 2).

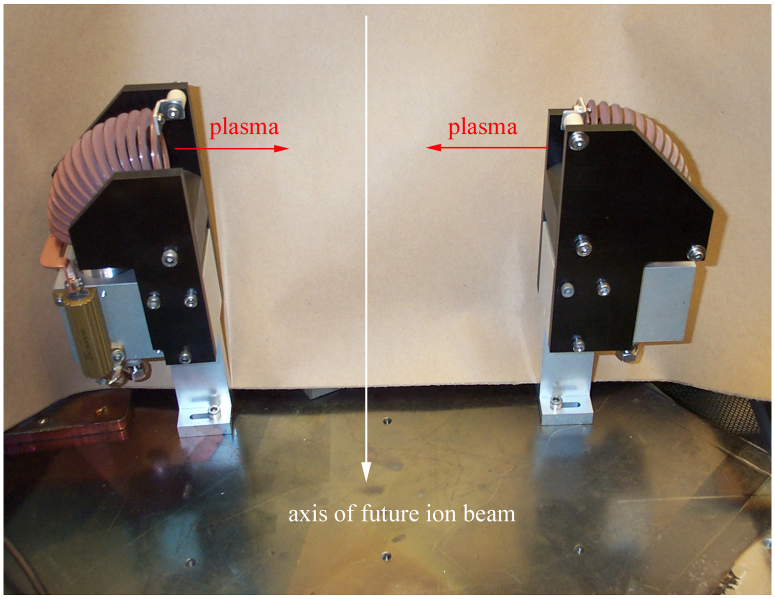

Figure 2: Two source units mounted in vacuum chamber for tests.

A large ion collector, a plane, isolated sheet of stainless steel, was positioned between the sources. The collector as biased negatively to repel electrons and collect ions. A typical trace is shown in Fig.3, taken at a base pressure about $5x10^{-6}$ Torr.

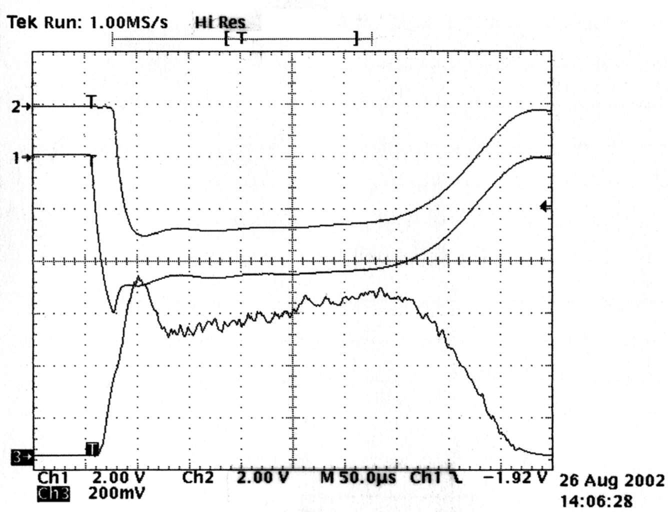

Figure 3. Arc current pulse of the two arc sources (0.01 A/V) shown by channel 1 and 2, and aluminum ion current as collected by a biased plate, channel 3, 0.1 A/V.

The ion current is noisy, as it is typical for vacuum arcs. It is anticipated to use the ion current at about 250 µs after arc triggering, i.e. just before the second maximum of the ion current. The value at that time was measured for many shots to get information on statistical fluctuations. The result is shown in Figure 4.

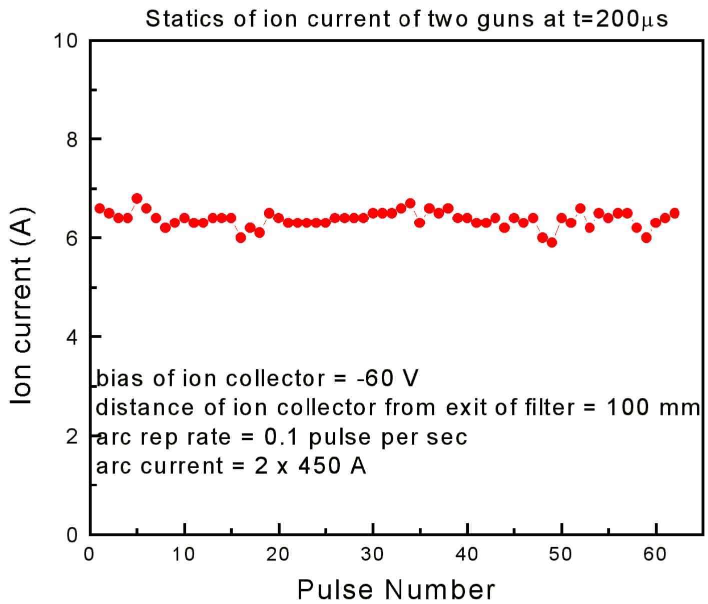

Figure 4. Ion current signal from two plasma sources, each operating with 450 A arc current, fed by the same PFN.

After these tests, the source units have been mounted to a large flange to be used at the beamline (Figure 5).

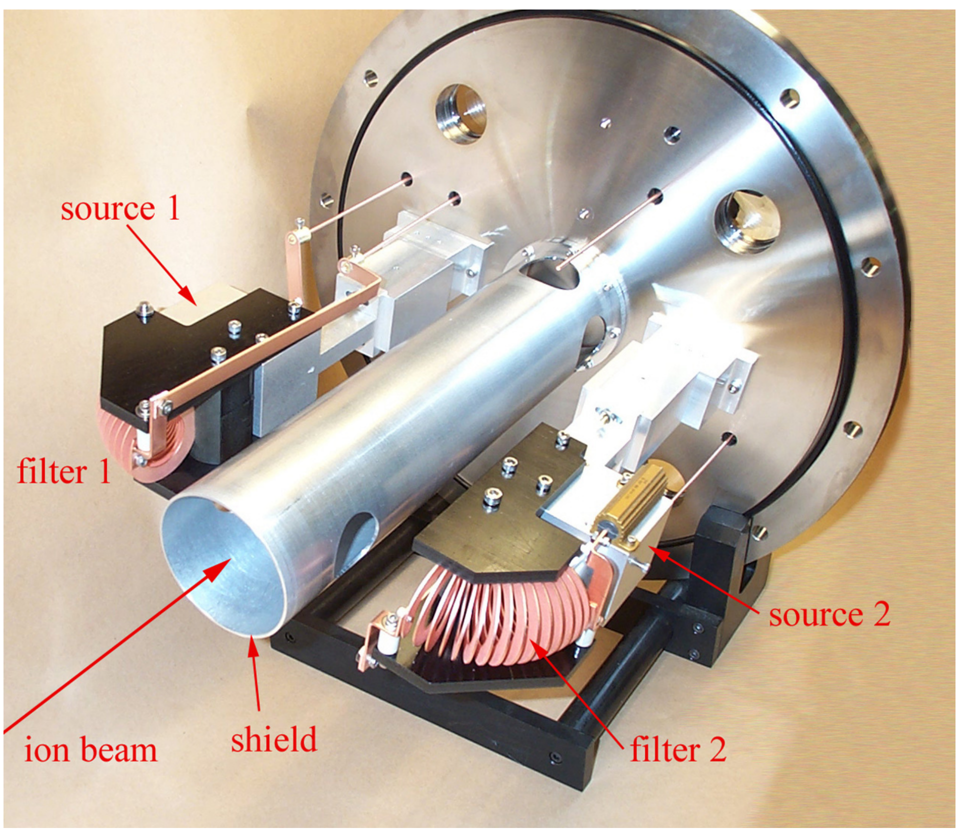

Figure 5: Plasma sources mounted with connectors. Plasma is injected in the path of the ion beam through openings in the aluminum metal shield. The shield is designed to reduced the magnetic field at the location of the ion beam, to reduce plasma entering the quadrupole region, and the prevent macroparticles from the source to enter the beam region.

The flange with sources and the beam shield was evacuated with a small turbomolecular pump to a base pressure of low 10^{-5} Torr. A temporary ion collector made form Mo sheet metal was mounted inside the shield to measure the plasma density in the presence of the shield. As one can see from Figure 6, the plasma density is about 20% of the previous measurements, which is attributed to plasma cut-off of the shield (plasma can enter only through the opening in the shield), and also the somewhat higher base pressure may have played a role. To demonstrate the shot-to-shot reproducibility, we show ten successive ion current pulses in Figure 6.

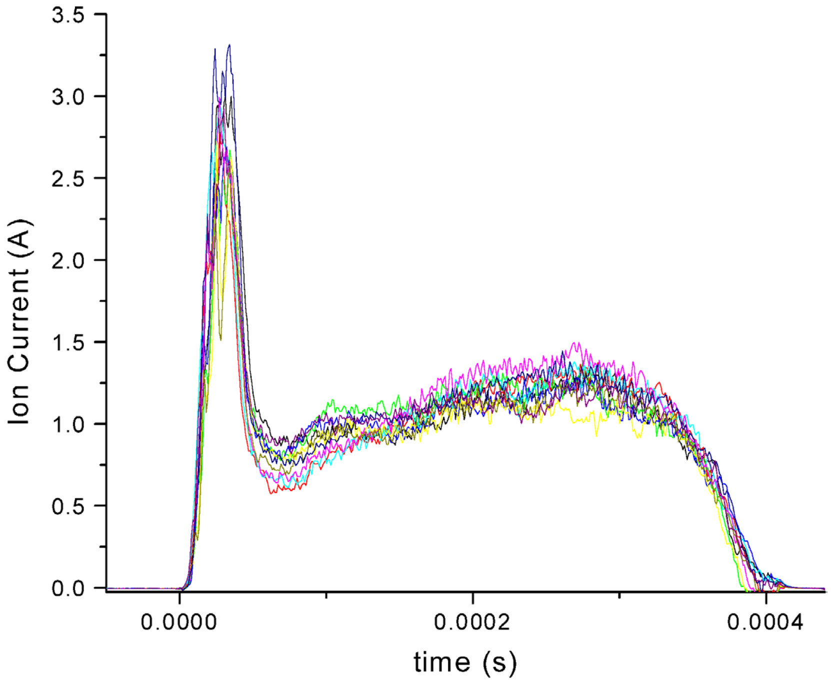

Figure 6: Aluminum ion current of ten successive arc pulses as collected by an ion collector placed inside the cylindrical shield, i.e. at the location of the future ion beam.

The plasma density can be estimated using the general formula

$$j_i = Q e n_i \bar{v}_i \tag{1}$$

where j_i is the ion current density, Q is the average charge state number, e is the elementary charge, n_i is the plasma (ion) density, and $\bar{v}_i$ is the average ion velocity in the direction of the collector, which is here identical with the plasma flow velocity. From the literature [4] we know that Q=1.7, $\bar{v}_i = 15,400$ m/s , and with an area of collection of about 10^{-2} m^2, one obtains

$$n_i \approx 1.8 \times 10^{16}\,\mathrm{m}^{-3} = 1.8 \times 10^{10}\,\mathrm{cm}^{-3}$$

as the average plasma density inside the metal shield at about 250 μs after arc triggering, at a PFN charging voltage of 2.0 kV. This density can be adjusted through a change of the distance between the filter exit and the beam shield, and by the arc current via the PFN charging voltage.

References.

[1] R. A. MacGill, M. R. Dickinson, A. Anders, O. R. Monteiro, and I. G. Brown, "Streaming metal plasma generation by vacuum arc plasma guns," *Rev. Sci. Instrum.*, vol. 69, pp. 801-803, 1998.
[2] A. Anders, "Approaches to rid cathodic arc plasma of macro- and nanoparticles: a review," *Surf. Coat. Technol.*, vol. 120-121, pp. 319-330, 1999.
[3] A. Anders, R. A. MacGill, and T. A. McVeigh, "Efficient, compact power supply for repetitively pulsed, "triggerless" cathodic arcs," *Rev. Sci. Instrum.*, vol. 70, pp. 4532-4534, 1999.
[4] A. Anders and G. Y. Yushkov, "Ion flux from vacuum arc cathode spots in the absence and presence of magnetic fields," *J. Appl. Phys.*, vol. 91, pp. 4824-4832, 2002.